NEW LOW-COST MANUFACTURING METHODS TO PRODUCE SILICON CARBIDE (SIC) FOR LIGHTWEIGHT ARMOR SYSTEMS

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ABSTRACT

Ceramic-based armors, commonly used in personnel protection, are actively being considered for platform vehicles due to their potential to dramatically reduce system weight. Silicon carbide (SiC) has been shown to hold considerable promise as the ceramic component in an armor system, and comes in several grades with differing costs. Hot pressed silicon carbide has been shown to provide excellent ballistic properties, but is manufactured at high cost and in limited volumes through a batch process. The U.S. Army Research Laboratory (ARL), through the ManTech Armor program, has developed a program with BAE-Advanced Ceramics Division, Vista, CA to dramatically reduce cost and increase production volume of hot pressed silicon carbide. BAE has built a prototype manufacturing system and recently conducted a one-ton manufacturing run to demonstrate cost and viability of the system. The material will undergo ballistic evaluation to determine if the ceramic produced using these new manufacturing techniques is equivalent to conventionally processed material.

This paper provides an overview of ceramic hot pressing, changes made through the ManTech program, cost goals and current status of the program.

1. INTRODUCTION

The ARL, through the Army's Armor ManTech program, is working with BAE-Advanced Ceramics Division to redesign their hot pressing process to dramatically reduce cost to a level comparable to pressureless sintered SiC. Changes at all stages of the manufacturing process were introduced, including a semi-continuous furnace that manufactures near net-shape tiles and rapid computer-controlled final grinding machines. These changes will not only reduce cost, but will allow for increased production volumes to the levels anticipated for future armor vehicle programs, since the ManTech manufacturing cell can be considered a simple unit cell that can be easily duplicated. The goal of this effort is to produce a SiC-N material with the same material properties and ballistic performance as that which is conventionally produced, but at a much lower cost in an automated semi-continuous process.

2. BACKGROUND

Ceramic-based armor, with either a metallic or polymer-matrix fiber composite backing, has been demonstrated to be a highly mass efficient armor design for common ground vehicle threats. Of the typical armor ceramics, aluminum oxide (Al_2O_3), boron carbide (B_4C), silicon carbide (SiC), titanium diboride (TiB_2), SiC has been shown to be the highest performing ceramic using current armor designs. These types of ceramics can be manufactured by several different methods, including hot pressing, pressureless sintering and reaction bonding. As is often the case, the fabrication route that is the highest cost (hot pressing) produces ceramics with the highest level of ballistic performance, and BAE Systems-Advanced Ceramic's SiC-N ceramic is considered to be the industry benchmark. Historically, hot pressing requires batch processing, consumable graphite tooling and the machining of densified billets into the desired tile shape, all of which contribute to the high cost and low production volumes of hot pressed ceramics.

3. TRADITIONAL CERAMIC HOT PRESSING

Ceramics are commonly densified through sintering with the concurrent application of pressure, and this process is known as hot pressing. The application of pressure promotes the closing of pores and allows for high densities to be achieved. Non-oxide ceramics, such as silicon carbide, silicon nitride and boron carbide are, are commonly hot pressed. Other ceramics can be densified to full density without the application of pressure, and this

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is known as pressureless sintering. Oxide ceramics are commonly manufactured through this method, but some non-oxide ceramics are doped with sintering aids to promote densification.

Sintering is a solid-state process whereby powder compacts are densified at temperatures sufficient to allow for diffusion but below the temperature for the material to melt. Therefore, atoms of material are transported to areas of porosity and pores are transferred to the outside, and this requires sufficient time and temperature for this all of this to occur. There are two main types of diffusion: (1) lattice diffusion and (2) surface diffusion. For surface diffusion, the driving force is the reduction of surface area of the particles and necks are formed between two contacting particles. Once the neck is formed and the driving force is reduced, the process slows resulting in very little densification, which is not desired. For lattice diffusion, material is transported through the ceramic particles and densification results. Since the cations and anions of each species have different diffusion rates for each type of diffusion, sintering is a very complex and scientifically rigorous process. Many ceramic systems can be densified without concurrent pressure (pressureless sintering) with the addition of sintering aids, which affect the diffusion constants. Hexoloy, St. Gobain, Niagara Falls, NY is a commercial silicon carbide produced by pressureless sintering. Based on the testing of a number of silicon carbide types, the hot pressed silicon carbides demonstrate superior performance.

Traditional hot pressing is a batch process, where the "green" (undensified) powder compacts are formed through some method with the ceramic powder and loaded into a hot pressing die. The die and powder are brought up to the sintering temperature and a load is applied to the die. Due to the very high temperature required for sintering, graphite tooling and specialized furnaces are required. Many of these non-oxide ceramics require sintering temperatures in excess of 2000oC. Figure 1 shows a typical laboratory hot press with a furnace chamber, hydraulic system to apply load, and a load frame. As the size of the ceramic part increases, the load required for desired pressure becomes quite large to provide the adequate pressure. This requires the hot pressing equipment to be very large, especially the load frame, thus making hot pressing process typically associated with small production volumes. Production volumes dictate that large billets be made instead of individual armor tiles, which are later sectioned into tiles. To increase throughput, commercial vendors typically stack a number of plates together with spacers and apply pressure to the entire stack. Another limitation to hot pressing is that the parts that can be produced are rather limited in shape, basically flat plates or plates with limited curvature, such as a Small Arms Protective Insert (SAPI) plate.

After hot pressing, the stack of ceramic plates is allowed to cool to room temperature. Since the armor tiles sizes tend to be rather small, the ceramic is typically hot pressed in large plates and tiles are machined from these billets. For companies that produce ceramics by sintering, they prefer to cut them in the "green" or undensified state, since the machining of ceramics tends to be expensive and time consuming.

Figure 1. Laboratory hot press consisting of a furnace chamber and hydraulic system to apply load

With common armor ceramics being some of the hardest materials known, machining requires diamond tooling and slow grinding rates and cutting steps. The billets are pressed to be somewhat over in thickness and a diamond surface grinder is used to grind the ceramic billet to exact thickness. The surface grinder usually makes a pass and then the diamond wheel is indexed downward by several thousandths of on inch. Figure 2 shows a typical surface grinder. The machine has diamond wheel that is fixed in the X and Y direction. The stage holding the billet is moved back and forth and indexes left and right to cover the whole billet is several passes. After the diamond wheel sweeps the entire billet, it is indexed downward in the z direction and the process is repeated. With these slow removal rates, it takes considerable time to grind the billet down to a desired thickness. Grinding can also introduce damage and cracks onto the surface as well as cause sub-surface damage.

Figure 2. Typical surface grinder with a diamond wheel

After the billet is ground to the correct thickness, the billet is sectioned to armor tiles of the desired shape and size. Surface grinding takes considerable time and effort to produce ceramic tiles; therefore, machining is a significant portion of the total cost of producing tile. For square tiles, the entire billet can be sectioned into tile, thereby giving a high yield. But for hexagonal tiles, rectangles of ceramic are sectioned from the billet and the corners are then removed to produce a hexagonal shape. Therefore, a significant portion of billet is not utilized, which results in a 50% price premium for these tiles. One benefit of diamond machining is that the dimensional tolerances are very good and superior when compared to tiles produced by pressureless sintering. Depending on the ceramic dimensional tiles required for future vehicle programs, tiles may need to be diamond machined regardless of how they are manufactured. Tile gap spacing is critical when a large array of tiles is put together, and this can quickly become a problem when tiles don't have a high degree of dimensional uniformity. This is more severe when tiles are hexagonal in shape. Ceramic tiles made by sintering alone are inherently less expensive to manufacture, but if they need to be machined for higher dimensional uniformity, than any cost saving will would be greatly diminished.

4. MANTECH HOT PRESSING SYSTEM

The ManTech low-cost tile program was formulated in 2002 to look at greatly reducing the cost associated with hot pressing tiles, and to build a system that could be more easily duplicated to meet the needs of much large production volumes anticipated for future vehicle programs. The major elements of this transformation were (1) the use of high speed computer-controlled machining, (2) a semi-continuous furnace that produces near net-shaped tiles. The most significant change is focusing on manufacturing tiles from start-to-finish to near net-shape, instead of large billets that are sectioned into tiles. Either a 4" square or a 4" flat-to-flat hexagonal shape were the tiles sizes the system was designed and optimized to efficiently manufacture. Producing just these small tiles allowed for the large load frame and large hydraulic system used in a conventional commercial hot press, Figure 3, to be replaced by a much smaller system. So the hot pressing chamber became rather small and not much larger than the laboratory-scale system shown in Figure 1. Since only small tiles need to be ground, the surface grinders were replaced by double-disk grinders, and these can grind a small areas (such as tiles) at a much faster rate and can grind two surfaces at one time. This allowed from machining times to drop significantly.

Figure 3. Commercial traditional hot press at BAE Systems

Since the ManTech processing produces near net-shaped tiles, some changes in the powder processing and forming were necessary. The most significant change was using dry pressing to form the "green" (undensified) ceramic preforms, this entailed mixing the ceramic powder with a binder and compacting the part in a die. To aid in the filling of the die, the powder was granulated to improve powder flow. Several other changes were made to powder processing with the goal of developing a process that could be scaled to much larger production volumes. Figure 4 shows the green compacts for hexagonal tiles at several thicknesses. The tiles maintained the same cross-sectional area, but were reduced in thickness when densified.

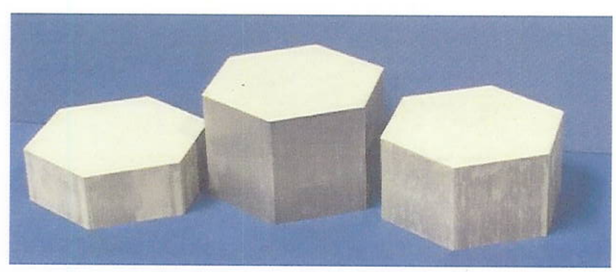

Figure 4 Hexagonal shaped preforms dry pressed to shape

The ManTech furnace was designed so that the hot pressing chamber is always at the hot pressing temperature and die sets containing the green compacts are automatically ramped up to temperature by stepping the die through a series of furnace chambers of varying temperature. The die is then stepped into the hot pressing chamber and the compact is densified under pressure and temperature. The system was designed to press four parts in each die. After the part has been densified, it is ramped down in temperature through a series of furnace chambers until the die is able to be handled. Figure 5 shows the ManTech furnace with a number of ramp-up and ramp-down chambers, as well as the hot pressing chamber in the center. Since the loads only need to be supplied to a small area, the load frame and hydraulic system is quite small compared to a commercial hot pressing operation. When the system is running, multiple dies sets (one in each chamber) are in the furnace; some are being ramping up in temperature, one set is being hot pressed, while others are cooling. The time it takes for the die set in the hot pressing chamber to be densified is the rate-limiting step.

Figure 5. ManTech hot pressing furnaces with multiple heating and cooling chambers, and a central hot pressing chamber

The surface grinders (used to grind billets down to desired thickness) were replaced by high-speed double-sides grinders that can rapidly removed grind stock, Figure 6. The tiles are pressed to dimensions slightly larger than the 4" desired size, and then they are ground to the desired thickness. The edges are ground to thickness, two sides at a time. Therefore, the tiles are never diamond sectioned to the appropriate size, only ground to size. Since they are ground to final size, the tiles can be measured for thickness during grinding to reduce the potential of producing out-of-spec parts. The grinding system is automated and computer-controlled, and includes an optical gaging system to accurately measure tile size during then grinding operations. These additional machining features should increase tile yield. Also, by reducing the amount of grind stock removed during grinding is another potential way to further reduce cost.

Figure 6 Double-disc grinders implemented under the ManTech program. They are fully automated and computer controlled.

5. PRICING GOALS

Cost reductions and a processing system amendable to rapid scale at the two major goals of the program. Hot pressed silicon carbide is an expensive ceramic compared to sintered aluminum oxide and sintered silicon carbide. The conventionally produced SiC-N from BAE has a cost of $135/lb for a square tile, while a hexagonal tile (a 50% premium) is $200/lb. As of October 2006 with demonstration of the ManTech machining methods on billets conventionally manufactured and sectioned into tiles, the current cost of the material is $85/lb. The goal of the ManTech program, with the current ManTech current is a cost of $50 lb for both hexagonal and square tiles. Since the tiles are manufactured to near net-shape, there is no additional waste associated with the hexagonal tiles, which keeps the costs the same. There may be an additional cost associated with the hexagonal tiles, if there are issues of yield due to the grinding a more complex shaped part. This is a first-generation furnace, it is anticipated that the cost can be reduced further by reducing the amount of grind stock on the part and adding additional efficiencies in the furnace to increase throughput. The final goal would be to produce hot pressed SiC-N at $35/lb, which is a cost comparable to a sintered (unmachined) silicon carbide. Optimizing the furnace design to meet these goals may require a new furnace to be built.

Table I Cost goals for the ManTech process compared to the conventionally processed SiC-N for two tile shapes.

	Conventional ($/ lb)	Current (Conv. w/ManTech Machining) ($/ lb)	Full ManTech Process ($/ lb)	Final goal ($/ lb)
4" X 4" tile	135	85	50	35
4" flat-to-flat hex	200	125	50	35

6. PROCESSING ISSUES

After several years of redesigning the hot pressing process and ordering new equipment, the start-up operation of the ManTech furnace was a major milestone in July 2007. Initial tiles manufactured with the furnace contained undesirable features that resulted from ceramic processing issues inherent in the SiC-N formulation. These tiles contained regions of low density, or "white edge," Figure 7, on and near the surface. This is due to chemical reactions in the material at the high temperatures seen during sintering. At these temperatures, the loss of sintering aid in the near-surface regions of the tile retarded the densification process. While some white edge is acceptable on the near net-shaped tiles, it should be completely ground away during final machining, since the white edge material has been shown to have degraded ballistic properties.

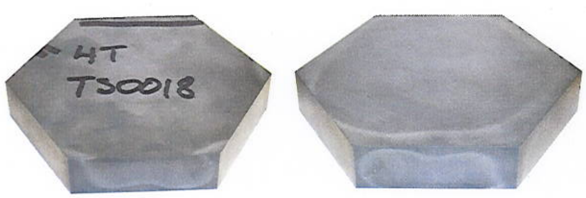

Figure 7. White edge region shown in initial group of ManTech tiles ground to final size

In the fall of 2007, a series of design-of-experiments were conducted to reduce and eliminate this white edge problem by better controlling the atmosphere and slowing the loss of sintering aid in the near surface regions. By the spring of 2008, several of these modifications allowed for the fabrication of tiles with no or very minimal amount of white edge on tiles after final machining.

7. CURRENT STATUS

After the white edge problem was solved on the ManTech tiles and furnace conditions for a large production run were determined, an important component of the furnace broke and it took several months to fix. With the furnace back in operation in June 2008 and producing ceramic of good quality, the one-ton campaign run was commenced to determine actual productions costs to compare to the cost estimates. The production run occurred in July and August 2008. Approximately 1500 tiles were produced under this run and all of the tiles were tracked from powder compacts, to binder burnout, and finally position in the run. Density of the tiles was measured before and after machining along with several other parameters, and compared to previously determined yield criteria. A statistical analysis is being conducted to look at trends in the processing conditions to determine subtle changes in processing that affect quality and final yield. A cost analysis for the run will be conducted to compare against the cost estimates (Table 1). In the fall of 2008, a significant number of tiles will be selected for ballistic qualification testing. The goal is to provide equivalent ballistic performance compared to conventionally processed material, but at a much lower price.

8. Future Efforts

If the ballistic properties of the ManTech SiC are shown to the equivalent to conventionally processed SiC-N, then it is planned that BAE will conduct another one-ton run on a different composition of hot pressed SiC. They will also investigate the possibility of manufacturing a number of individual small tiles in the same die used for the current tiles. This would allow the same system to efficiently produce tiles of different sizes. Currently, the system is optimized to produce only 4" square and hexagonal tiles, while other sizes would reduce production yield. Also, the system designed here is a first-generation system and overall efficiency would be improved if the lessons learned with this system were incorporated into a second-generation furnace

9. SUMMARY

Silicon carbide is an important ceramic material that may be used for future ceramic-based armor systems. Based on performance, hot pressed silicon carbide is of great interest, but high production costs and limited production volumes may limit the use of this material. Therefore, a ManTech program was initiated to explore ways to dramatically reduced cost and provide a manufacturing system that could be easily duplicated to meet anticipated needs. A first-generation ManTech line has been built and recently produced one ton of silicon carbide tiles. The cost estimates of the process are being verified on this run, and the material will be ballistically evaluated in the fall of 2008 to compare against conventionally processed material. The goal is to produce a silicon carbide with equivalent performance to the industry-standard SiC-N, but at a much lower cost.

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